

# **Solid Oxide Fuel Cell Hybrid System for Distributed Power Generation**

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## **Abstract**

This report summarizes the work performed by Honeywell during the April 2002 to June 2002 reporting period under Cooperative Agreement DE-FC26-01NT40779 for the U. S. Department of Energy, National Energy Technology Laboratory (DOE/NETL) entitled "Solid Oxide Fuel Cell Hybrid System for Distributed Power Generation". The main objective of this project is to develop and demonstrate the feasibility of a highly efficient hybrid system integrating a planar Solid Oxide Fuel Cell (SOFC) and a turbogenerator.

For this reporting period the following activities have been carried out:

- Conceptual system design trade studies were performed
- Part-load performance analysis was conducted
- Primary system concept was down-selected
- Dynamic control model has been developed
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## **Executive Summary**

This report summarizes the work performed by Honeywell during the April 2002 to June 2002 reporting period under Cooperative Agreement DE-FC26-01NT40779 for the U. S. Department of Energy, National Energy Technology Laboratory (DOE/NETL) entitled "Solid Oxide Fuel Cell Hybrid System for Distributed Power Generation". The main objective of this project is to develop and demonstrate the feasibility of a highly efficient hybrid system integrating a planar Solid Oxide Fuel Cell (SOFC) and a turbogenerator.

The hybrid system is based on Honeywell planar SOFC and turbogenerator power technologies. The planar SOFC is based on thin-electrolyte cells and metallic foil interconnects. This technology leads to SOFC stacks that operate at reduced temperature (<800°C) and have reduced materials cost. This work will culminate in testing of a small SOFC-based hybrid system that will incorporate all of the components/subsystems required for a full-fledged system.

The work consists of three phases and will focus on defining and optimizing a suitable system concept, conducting experiments to resolve identified technical barriers, performing cost analysis, and testing a small hybrid system to demonstrate concept feasibility.

The various phases and tasks to be performed under this program are attached. For this reporting period the following activities have been carried out:

- Conceptual system design trade studies were performed
- Part-load performance analysis was conducted
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## **Approach and Results**

### **1. TASK 1A.1 – SYSTEM DESIGN**

#### **1.1 SUBTASK 1A.1.1 – DESIGN CONCEPT DEVELOPMENT.**

Trade studies on conceptual system design candidates were during the reporting period. The influence of system parameters on the system efficiency was analyzed in detail for two concept candidates. The system candidate with the highest system efficiency was selected for the future system design. A preliminary part-load performance analysis of the selected system candidate was also conducted.

### 1.1.1 Conceptual System Design Trade Studies

The proposed conceptual system design candidates are shown on Figures v2-1 through v2-3 (presented in EPACT protected volume). The concepts were described in detail in the previous quarterly report. Concept 2 has a drawback of a lower efficiency but an advantage of the atmospheric pressure operation, which results in less stringent requirements on the fuel cell materials. Due to its lower efficiency however, this concept was eliminated prior to detail system studies.

### 1.1.2 Efficiency Screening Calculations

Concepts 1 and 3 were analyzed to determine parameters that affect the system efficiency. A two-level Design of Experiment (DOE) was performed for each concept to screen for the extent of the effects of each parameter as well as those of any parameter interactions on system efficiency. A regression of the DOE results was then conducted to create efficiency transfer functions, i.e. the dependence of the system efficiency on critical system parameters, for each concept.

The average fuel cell temperature was fixed at 800°C. The system efficiency at the peak power point, corresponding to the peak turbogenerator speed of around 65 krpm, was only considered. There is no guarantee that the results presented below would be valid at part-load operating points. However, the system design approach calls for the optimal efficiency at the peak power, therefore the detailed optimization studies will be done only at this design point. The system efficiency sensitivity at part-load operating points will be revisited during the part-load analysis activities.

Aspen Plus system models for Concepts 1 and 3 were created earlier in the program to analyze the effects of system parameters on the system performance. The models included the turbomachinery and the fuel cell performance models created earlier.

The efficiency transfer function for Concept 1 was reported in the previous period:

(eq. v2-1) {presented in EPACT protected volume}

where

$\eta$  = System Efficiency;

$j$  = Current Density;

$T_{ref}$  = reformer temperature;

$U_f$  = fuel utilization

$T_{rec,in}$  = recuperator hot side inlet temperature

SCR = reformer steam-to-carbon ratio

The efficiency transfer function for Concept 3 was developed during the reporting period. Six parameters were identified as having large effects on the system efficiency: the fuel cell current density; the reformer temperature; the fuel utilization in the fuel cell; the turbine inlet temperature; the reformer steam-to-carbon ratio; and the fuel flow rate. The inclusion of the fuel flow rate as an independent parameter underscores the fact that this system has a higher flexibility of varying the fuel cell power relative to the airflow rate from the compressor than in Concept 1. In Concept 1, the fuel flow is fixed for a specified combination of the turbine speed and the five parameters listed in Table v1-1. In Concept 3, the fuel cell is downstream from the turbine, and the fuel cell performance does not directly affect the turbine inlet temperature. This in effect decouples the turbine inlet temperature and the fuel flow rate and allows the turbine inlet temperature to vary.

The following table shows the ranges for each of the variables analyzed in the DOE.

Table v1-1. Parameters affecting the system efficiency of Concept 3

Variable	Low Limit	High Limit
Current Density, A/cm <sup>2</sup>	0.2	0.3
Reformer Temperature, °C	600	700
Fuel Utilization	0.65	0.85
Turbine Inlet Temperature, °C	870	980
Steam-to-Carbon Ratio	1.5	3.5
Fuel Flow Rate, kg/hr	36	54

The full-factorial DOE was conducted by analyzing the system performance at the 64 different combinations of the system parameters and computing a regression of the resulting system efficiency distribution. The regression analysis yielded the following transfer function for Concept 3:

(eq. v2-2) {presented in EPACT protected volume}

where

$\eta_3$  = system efficiency of Concept 3;

$T_{tur,in}$  = turbine inlet temperature;

SCR = reformer steam-to-carbon ratio;

$w_{NG}$  = natural gas inlet flow to the system.

Some of the three-level interactions are present in Equation (v2-2), unlike the system efficiency regression for Concept 1 (Equation (v2-1)).

The effects on the system efficiency discussed for Concept 1 are also present in the system efficiency regression for Concept 3. An additional effect of the fuel flow rate on the system efficiency is present in Equation (v2-2), however it is rather small. The stack temperature rise constraint rather than efficiency considerations will determine the maximum fuel flow rate in Concept 3.

Optimization of Equation (v2-2) subject to design constraints resulted in the baseline conceptual design for Concept 3. The details of the design are shown in Table v2-2. As Table v2-1 indicates, the system efficiency of Concept 3 design is about 52.77% and the system peak power is just below 400 kW.

The total power of Concept 3 is lower than that of Concept 1 although the air and fuel flow rates are similar. There are two main reasons for that

- (1) The fuel cell operates at a higher pressure in Concept 1 than in Concept 3, which results in higher fuel cell voltage per cell in Concept 1 and hence, higher fuel cell power.
- (2) The turbine power is higher in Concept 1 because both the fuel and the water inlet mass flows end up expanding in the turbine and contributing to the turbine power, unlike Concept 3, where only the air flow expands in the turbine.

The same two effects are responsible for the higher system efficiency in Concept 1. The fact that the natural gas compression power is much lower in Concept 3 than that in Concept 1, due to operating at atmospheric pressure, proves to be insignificant for the system efficiency comparison.

### 1.1.3 Concept Down-Selection

Overall, Concept 1 is the preferred approach between the two concepts if the system efficiency is the only design output. The situation may be somewhat different if other criteria are included in the decision process. Concept 3 may have an advantage over Concept 1 in the installed cost, the system reliability and availability, the system lifetime, and possibly other parameters. On the other hand, Concept 3 requires the availability of a high temperature and high differential pressure microturbine-fuel cell heat exchanger. The development of such a device is a high risk to the overall development of Concept 3, as the temperature range of operation (in excess of 1900 °F) represents a challenge for material selection.



#### 1.1.4 System Part-Load Analysis

A part-load performance analysis was performed for Concept 1. The fuel cell performance model and Parallon 75 component maps describe the part-load performance of the fuel cell and the microturbine respectively. Conservative estimations about the performance of the reformer and the balance of plant were made for this study. The reformer temperature and the steam-to-carbon ratio, the fuel utilization and the recuperator inlet temperature were kept constant across the operating range.

The resulting system efficiency as a function of the net system power is shown on Figure v1-1. The efficiency steadily rises with the power and reaches its maximum point at the peak power point. (Note that Equation (v2-1) is not applicable to the part-load system efficiency because it was developed specifically for the peak microturbine speed). As Figure v1-2 indicates, the fuel cell power rises at a higher rate with the microturbine speed than does the microturbine power. Since the fuel cell is more efficient than the microturbine, this results in higher total system efficiency as the total power increases.

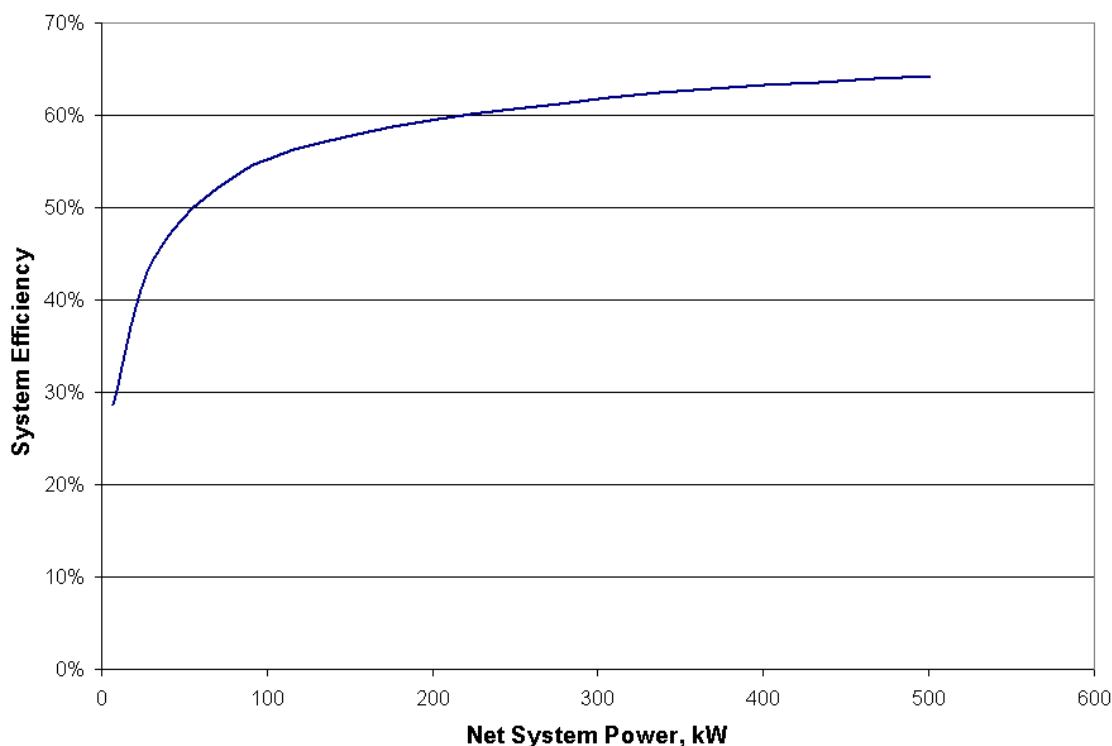


Figure v1-1. System Efficiency as a function of Net System Power, Concept 1

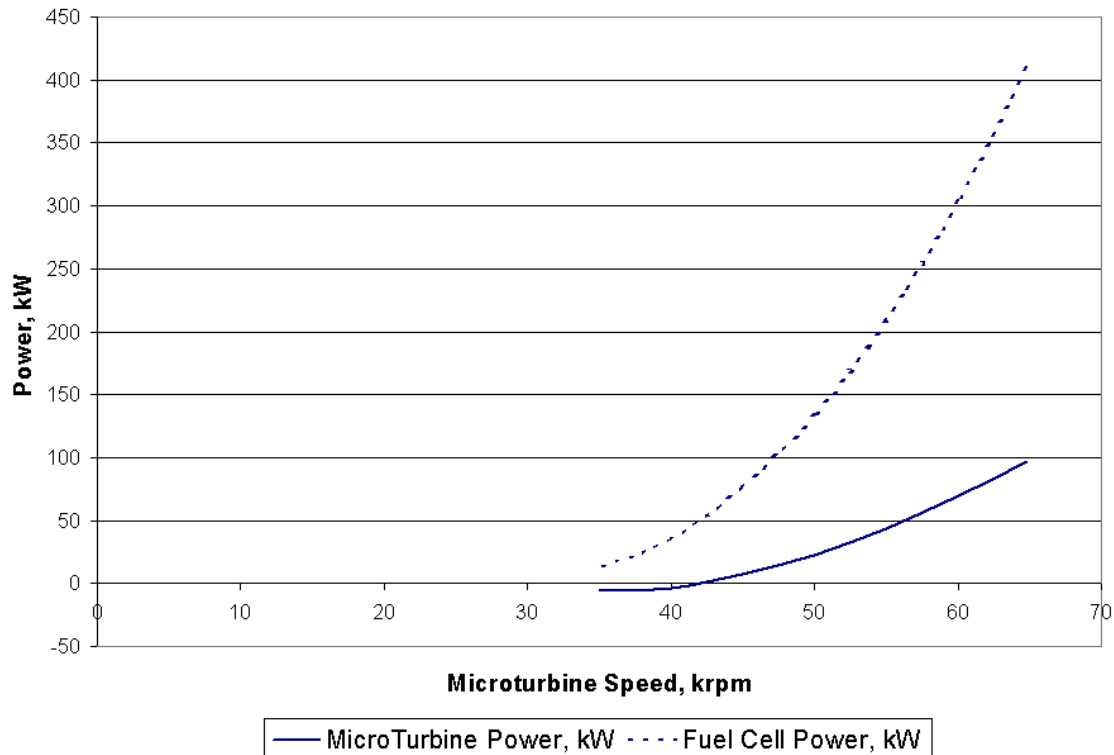


Figure v1-2. SOFC and MT generated power vs. MT Speed, Concept 1

## 1.2 CONTROL SYSTEM DEVELOPMENT

### 1.2.1 System Control Approach

The control system will provide the operator with the ability to automatically step through the startup sequence, regulate to commanded load demand points, step down through the normal shutdown sequence, perform basic health monitoring of the system, and handle emergency shutdown of the system. A dynamic model of the system has been developed using GE Hybrid Power Generation System's proprietary library of fuel cell system component models, and will be used to design and evaluate various control strategies prior to hardware implementation. The design of efficient controls for the fuel cell system requires consideration of many factors, significantly:

- With potentially wide load fluctuations, the controller should be able to maximize efficiency in different operational regions, and under different operating conditions. These include conditions that occur during startup, steady state operation and shutdown.
- The controller should be able to regulate power and voltage during steady state operation and maximize efficiency at setpoint.

- The controller should be able to minimize thermal stress and fatigue and limit component duty cycles that adversely affect the lifetime of the equipment.

In addition to the basic control functions, the controller will provide built-in test (BIT) and health monitoring around the system. The BIT will monitor sensors throughout the system and trigger alarms to shutdown the system if a sensor exceeds the specified operating range. Corrective and protective action will be programmed into the BIT to handle various failure modes or unscheduled events.

Figure v1-3 shows the design for control process that is being used for control system development. The controls task is currently in the Controls Requirements Definition process block. During this stage of the process system models are being developed, subsystem models are being developed and analyzed, the control loop analysis is being conducted to determine the dominant dynamic interactions in the system, and preliminary controls requirements are being formalized. The second quarter of 2002 has been primarily focused on building the dynamic system model and negotiating with other task teams on requirements for the system and various subsystems.

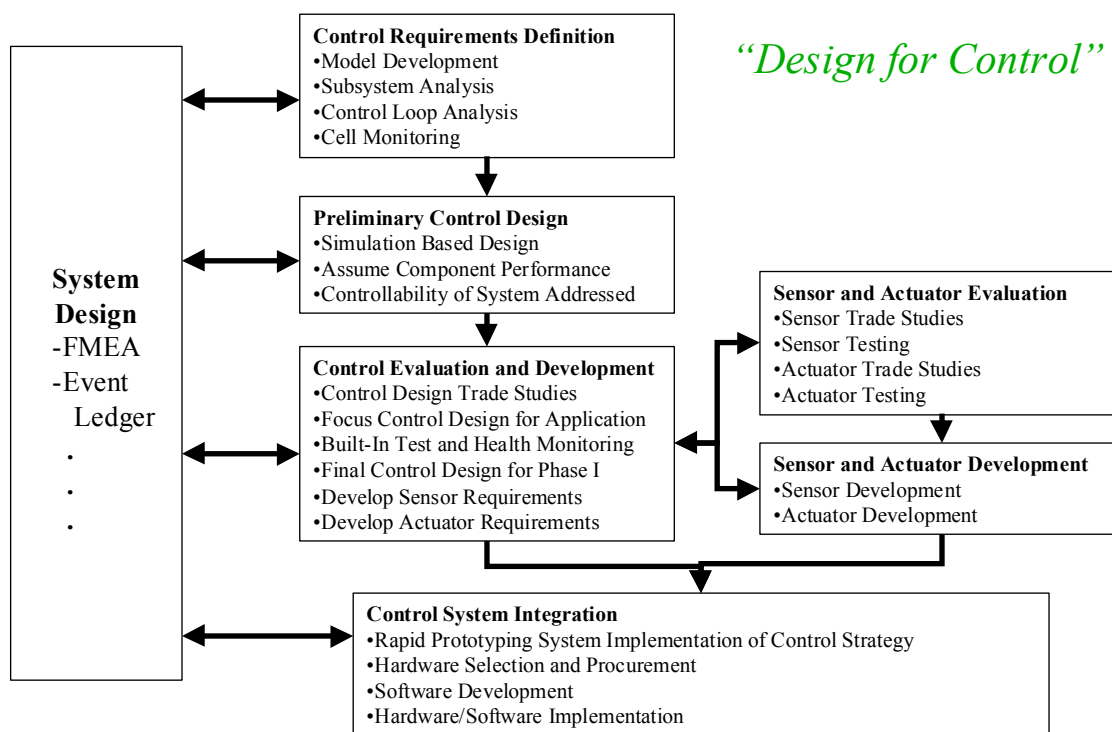


Figure v1-3: Controls Design Process

## 1.2.2 Control System Development

A dynamic system model of the conceptual system has been assembled using GE Hybrid Power Generation Systems' proprietary Fuel Cell Dynamic Component Library (Figure v2-4). This model will be used to determine significant dynamic interactions within the system, perform various component and system level trade studies, and to develop the control system design. The model will be updated to allow dynamic issues to be addressed as the system design changes and matures. This approach minimizes costs by reducing hardware tests and the risk of damaging components. The primary focus during Q2 has been on design of the feedback controls to provide load point regulation and safe transition between various load points.

## 1.2.3 Sensor and Actuator Evaluation and Development

The hybrid fuel cell system will have temperatures as high as 1100°C in crucial portions of the system. To control the system it may therefore be necessary to use high temperature sensors and actuators in portions of the system. The control system design will seek to minimize the use of high temperature sensors and actuators to reduce cost and maximize the reliability of the system.

Sensor and actuator requirements will be generated using the dynamic system model once the preliminary control design is created. Sensors will be evaluated in terms of their dynamic response, accuracy, operating environment requirements, and cost. Where the cost of a sensor is prohibitive for a production fuel cell system, the use of alternative sensors will be investigated as part of an indirect estimation technique to serve a similar function. A sensing strategy will be employed to create a cost effective, accurate, and fast responding set of sensors to indicate the state of the system to the controller.

Actuators will be evaluated in terms of their dynamic response and cost. This evaluation will seek to find low cost production grade valves that meet the temperature requirements for the different points in the fuel cell system. By considering controllability of the system from the initial stages of the system design, the requirements for the actuators in the system should be able to be relaxed and the robustness of the system improved.

The preliminary sensor survey has shown that many off-the-shelf sensors exist that can be used directly or modified for use in the hybrid system. The conclusion of this survey is that sensors should not be a high risk item for the control design, but further work will be needed in this area as the control design matures and cost targets for the control system are addressed. The preliminary actuator survey has shown that while there are many off-the-shelf valves that might fit the conceptual design, further definition of the system is needed before the risk of finding high-temperature actuators can be quantified. The sensor and actuator will be assessed continually through the control system design process.

## 2. TASK 1A.2 – TECHNICAL BARRIER RESOLUTION

### 2.1 SUBTASK 1A.2.1 – HIGH-TEMPERATURE HEAT EXCHANGERS.

In this period of performance, the focus of this task was on designing thermal management components for the HYBRID demonstration unit. Thermal management subsystem includes three heat exchangers, namely, recuperator, air preheater and reformat preheater (see system schematics, Figure v2-1 – v2-3). Preliminary designs of these heat exchangers are presented in Table v2-3. The requirements on these heat exchangers included high effectiveness and compactness that will result in low-cost designs. The pressure drops in the heat exchanger flows were kept to the minimum possible to reduce the parasitic power losses, and consequently increase the system efficiency.

### 2.2 SUBTASK 1A.2.2 – PRESSURIZED SOFC

#### 2.2.1 Endurance Test

In this reporting period, works has been focused on cell endurance test under pressure. Performance degradation under different pressure and different fuel utilization was evaluated and presented in Figures v2-7 and v2-8. For example, Figure v2-7 shows the cell performance degradation rates at current load of  $0.287\text{A}/\text{cm}^2$  under pressure of 2 atm. Significant difference in degradation rates was observed from these two tests. In general, the higher the fuel utilization, the higher water vapor pressure generated at the anode side, thus the more oxidation of interconnect. However, it might be premature to draw conclusions from these tests.

#### 2.2.2 Scale-up

Design for additional pressurized SOFC test stands to accommodate larger cells is being initiated. The design will include pressure vessel, various through-hole fittings, pressure control, built-in heating elements, and furnace control.

### **Summary**

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